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Emissions and Absorption of CO_2 in China's Cold Regions

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Abstract: Energy production and consumption are dominant sources of CO_2 emissions. Investigating the amount and characteristics of CO_2 emission sources can aid in reducing CO_2 emissions from energy-related sectors, which could lead to the development of advanced technologies and ideas for abatement. Cities play a significant role in CO_2 emissions, representing a distinctive unit with a specialized energy consumption structure, meteorology, economy, agriculture, forest acreage, etc. Those properties interact and influence CO_2 emissions. The city-level emission inventory is an important scientific database helping to investigate emission abatement technologies and establish control strategies. In this study, city-level CO_2 emissions and ecological absorption of China's coldest province are quantified. In the targeted region, winter lasts for about 6 months. Sectors of industry, thermal power generation, and domestic heating are dominant contributors to the total emissions. The provincial CO_2 emissions from energy consumption increased gradually, reaching 327.61 million tons in 2019. Cities with strong industrial activities produced higher CO_2 emissions. Moreover, the targeted region is a strong agriculture province, with the largest contribution to grain production in China. The absorption of farmland and forest was quantified, at 343.91 and 69.3 million tons in 2019, respectively. The total absorption was higher than the energy-related emissions. This indicated that the targeted region would provide a considerable carbon sink, attributed to the properties of its ecological system. From 2017 onwards, small boilers (single boilers smaller than 32 steam tons) were removed, and hence the emissions were lower than the original value. This study presents the characteristics of CO_2 emissions, and reveals the co-benefit of air pollution control on CO_2 reduction.

Keywords: energy-related emissions; CO_2 emissions; city-level inventory; cold region; ecological absorption

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Citation: Song, W.; Zhu, Z.; Yao, W.; Gao, Z.; Chen, R.; Zhao, Y.; Wang, M.; Wang, X.; Li, C.; Liang, M.; et al. Emissions and Absorption of CO_2 in China's Cold Regions. *Processes* **2023**, *11*, 1336. https://doi.org/10.3390/pr11051336

Academic Editor: Farooq Sher

Received: 20 March 2023
Revised: 23 April 2023
Accepted: 25 April 2023
Published: 26 April 2023

1. Introduction

Climate change is one of the most significant challenges facing humanity today, with its impacts being felt across the world in both natural ecosystems and human society. Scientific research has demonstrated the significant impacts of climate change, and the sixth report of the Intergovernmental Panel on Climate Change (IPCC) projected that the global temperature will rise by 1.5 °C over the next two decades due to the emissions of greenhouse gases, particularly carbon dioxide and methane [1,2]. As a result, there has been a growing recognition of the need for concerted efforts to reduce greenhouse gas emissions and mitigate the impacts of climate change.

Energy consumption is one of the primary anthropogenic sources of CO_2 emissions, resulting from various human activities such as burning fossil fuels, industrial processes, and forest vegetation destruction. The structure of energy consumption in different regions has a significant impact on the characteristics of CO_2 emissions [3]. Cities are a critical unit for global climate action since the unique characteristics of each city, including its location, economy, population, meteorology, environment, and ecosystem, result in diverse energy consumption properties. Cities are responsible for 67–76% of global CO_2 emissions and energy consumption [4]. Therefore, quantifying city-level CO_2 emissions is crucial for effectively reducing CO_2 and mitigating climate change, considering the specificities of each city.

To effectively reduce CO_2 emissions, it is necessary to accurately determine the role that energy-related industries play in contributing to these emissions. While some research has been conducted on CO_2 emissions at the city level, the majority of these studies have been limited to megacities or provincial capitals, and therefore lack a comprehensive understanding of emissions on a broader scale [5–7]. CO_2 emissions were compiled in previous studies based on activity data and emission factors. These data were collected from categorized sources, including fuel combustion, farmland irrigation, burned biomass, and production of goods, etc. [5–9]. In this study, the methods for constructing city-level emission inventories were investigated, taking into account various local datasets. This study provides a city-level CO_2 emission inventory, and the scientific data provide useful information for policymaking to reduce CO_2 emissions in these cities.

This study aims to address the research gaps by focusing on the CO_2 footprint in China's coldest region. Many previous studies provided the methods for calculating CO_2 absorption in China, according to the categories of farmland, utilization of fertilizers, area of living wood, etc. [10,11]. Variations of regions referred to the meteorological conditions and agricultural activities. This paper also utilized IPCC guidelines to calculate CO_2 emissions and living wood and crop absorption methods to estimate the ecological absorption of CO_2. This assessment helps us to better understand the importance of promoting sustainable practices in Heilongjiang province to maintain its vital role as a significant carbon sink.

In this study, CO_2 emissions are calculated based on energy categories and endpoint sectors, and the computation methods of the emission inventory are verified according to local parameters. Additionally, this study takes into account the agriculture sector, which is also an important anthropogenic source of CO_2 emissions. Furthermore, as the targeted cities are located in a strong agricultural province with special meteorological conditions, the carbon sinks of the province are also quantified. These factors are essential for understanding the carbon footprint of the targeted cities and provide useful information for policymakers to develop effective policies to reduce CO_2 emissions in these cities.

This research also provides methods for city-level CO_2 emission inventories that can be used in other regions globally. It highlights the need for more localized and context-specific approaches to CO_2 emission reductions, considering the unique characteristics of each city. The research findings could also be used to guide policymakers in the development of effective climate change policies and strategies that consider the unique characteristics of their respective cities.

2. Methodology

2.1. Target Region

Heilongjiang Province is located in Northeast China (121°11′–135°05′, 43°26′–53°33′), with special meteorology. The winters of Heilongjiang Province last for 6 months, with ambient temperature differences of more than 60 °C. The lowest temperature reached −50 °C. Energy consumption equaled 115.25 million tons of standard coal in 2020 [12]. Heilongjiang Province is known as a strong agriculture province, contributing to 56% of China's agriculture. The forest acreage is 46% of the total, and the area of living wood is about 1500 million km^2, which would play an important role in carbon absorption.

2.2. City-Level CO_2 Emission Inventory

City-level CO_2 emission sources in cold regions are categorized into anthropogenic and natural sources. In terms of the distinct characteristics of meteorological conditions, the source classification in each category is specified (Figure 1). Heating is a significant source of CO_2 emissions, being is much higher in some areas than in others. Emissions from agriculture and wood occur at the relevant time of year. Hence, the emissions and absorption are subject to seasonal variation in China's cold regions.

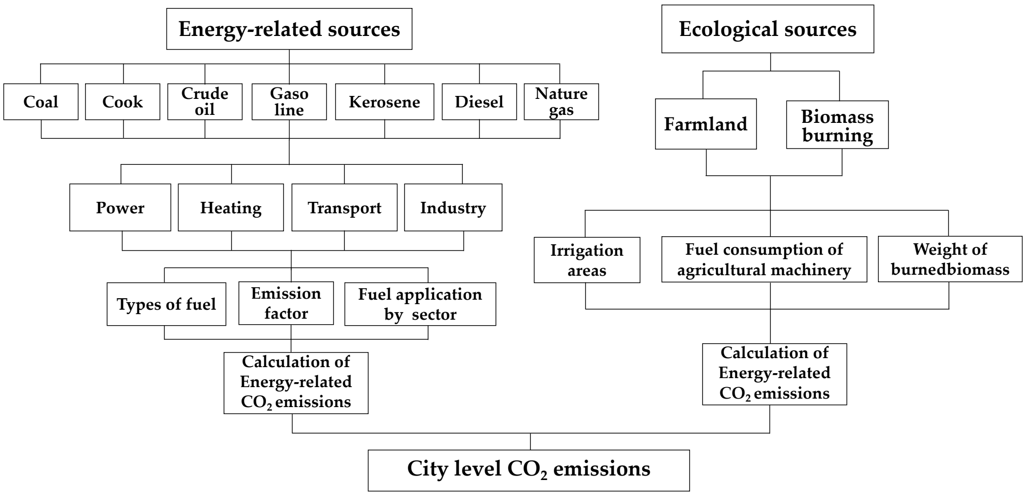

Figure 1. Source classification of CO_2 emissions in Heilongjiang Province.

A city-level CO_2 emissions inventory was built according to activity data and emission factors (Equation (1)). Activity data in the form of weight of fuel combustion, irrigation areas of farmland, amount of burned biomass, production of goods (e.g., cement, iron), etc., were mainly collected from the National Statistical Yearbook of China and the Heilongjiang Province Statistical Yearbook [12,13]. Emission factor data were available from National Statistical Organizations and recommendations from IPCC Reports [14], and previous studies [9,15].

$$\mathrm{E} = \sum \mathrm{A}_{\mathrm{i,j}} \times \mathrm{EF}_{\mathrm{i}} \tag{1}$$

where E represents the total CO_2 emissions of the targeted region; A refers to the activity data; EF represents the emission factors; i represents types of sectors; and j represents cities.

2.2.1. Energy-Related Emission Inventory

For energy-related sources, activity data were the fuel consumption by sector. Emission factors were the amounts of CO_2 emissions per unit of fuel combustion (Equation (2)). The net calorific value, emission factors, and oxidation efficiency were parameters associated with the properties of fossil fuels without big changes in the short term, which were uniform data for target years, adapted from previous studies [3,16]. The activity dataset was associated with the amount of energy production consumption and consumption.

$$\mathrm{E_e} = \sum\nolimits_{\mathrm{i}} \sum\nolimits_{\mathrm{j}} \mathrm{AD_{ij}} \times \mathrm{NCV_i} \times \mathrm{EF_i} \times \mathrm{O_{ij}} \tag{2}$$

where E_e represents CO_2 emissions of energy consumption; i represents the categories of energy, $i \in [1, 17]$; j is the types of sectors, $j \in [1, 48]$; AD_{ij} is the energy consumption of sector j [3]; NCV_i is the net calorific value of fossil fuel i; EF_i is the CO_2 emission factor of fossil fuel i [17]; and O_{ij} is the oxidation efficiency [3].

2.2.2. Industrial Process

Industrial processed included cement, iron, and ammonia production [6,7]. The activity data were adapted from the local statistical yearbook [1,16]. Emission factors were detected according to the products, which represent the amount of CO_2 emissions by the unit mass of goods production (Equation (3)) [8,18,19].

$$\mathrm{E_p} = \sum\nolimits_{\mathrm{p}} \mathrm{AD_p} \times \mathrm{EF_p} \tag{3}$$

where E_p represents CO_2 emissions of industrial processes; p represents the types of industrial processes; AD_p refers to the output of cement, iron, and ammonia; EF_p is the emission factors of industrial processes.

2.2.3. Farmland Ecosystem

CO_2 emissions of the farmland ecosystem are emitted from five sectors [10,11], including applications of chemical fertilizer, pesticide, agricultural film, farmland irrigation, and agricultural machinery (Equations (4) and (6)) [20–22]:

$$E_{irri} = AD_f \times EF_f \times \frac{44}{12} \tag{4}$$

$$E_e = (S_e \times EF_s + W_e \times EF_w) \times \frac{44}{12} \tag{5}$$

$$E = E_{irri} + E_e \tag{6}$$

where E_{irri} represents the emissions from the farming process; i represents the process of fertilizer and pesticide administration, agricultural films, and farmland irrigation; e represents the agricultural machinery; E is the total emissions of the farmland ecosystem; AD_f is the application amount and irrigation areas; S_e is the planting area of crops; W_e is the power of the agricultural machine; EF_f represents the emission factors of fertilizers, pesticides, agricultural films, and farmland irrigation; EF_s is the emission factors of crops [10,11]; and EF_w refers to the emission factors of agricultural machinery [10,11].

2.3. Emission Factors

Emission factors of energy-related factors are the amounts of carbon oxidized per unit of energy consumed [16]. For other sectors, emission factors correlate with products of industrial processes (cement, iron) and farming activities (fertilizing, irritation, machinery, etc.). The emission factors of CO_2 were adapted from previous studies [10,11,16], and are illustrated in Table 1.

Table 1. Emission factors for sectors.

Sectors	Emission Factors	Units
Coal	0.491 [16]	tCO_2/ton
Oil	0.838 [16]	tCO_2/ton
Natural gas	0.590 [16]	tCO_2/thousand m^3
Cement	0.074 [16]	tCO_2/ton
Iron	0.04 [8]	tCO_2/ton
Fertilizer	0.89 [10,11]	tCO_2/ton
Pesticide	4.93 [10,11]	tCO_2/ton
Farm films	5.18 [10,11]	tCO_2/ton
Machinery	0.18 [10,11]	kg/kW
Irritation	266.48 [10,11]	kg/hm^2

2.4. CO_2 Absorption

2.4.1. Farmland Ecosystem

CO_2 absorption was calculated for the whole growth period of crops in the farmland ecosystem (Equation (7)):

$$C = \sum\nolimits_i C_i \times Y_i \times (1 - W_i) \times (1 + R_i)/H_i \times \frac{44}{12} \tag{7}$$

where C refers to the CO_2 absorption of crops; i is the type of crop; C_i is the absorption rate of crop i; Y_i is the economic production of crop i (Heilongjiang Province Statistical Year

Book); W_i is the water content of crop i; R_i is the root to shoot ratio of crop i [10,11]; and H_i is the economic coefficient of the crop i [23–26].

2.4.2. Living Wood

This paper mainly considers the absorption of CO_2 by living trees (i.e., arbor trees, scattered trees, side trees, and sparse forests) (Equation (8)):

$$\Delta E = V \times (GR - CR) \times SVD \times BEF \times 0.5 \times \frac{44}{12} \quad (8)$$

where ΔE refers to CO_2 differences between the emission and absorption of living wood (net absorption in this study); V is the accumulation of living wood; GR is the annual growth rate of living wood; CR is the annual consumption rate of living wood; SVD is the density of wood; and BEF is the weighted average biomass conversion coefficient.

3. Results and Discussion

3.1. Total CO_2 Emissions in Heilongjiang Province

Heilongjiang Province is a typical cold region in China. It has the longest winter in China, the lowest ambient temperature reaches −50 °C in certain areas, and the heating services are required for 6 months. The statistical data on energy consumption have been recorded since 1995. Emissions of CO_2 increased over time. The annual increase rate was 24.16%. In 2019, CO_2 emissions reached 327.61 million tons (Figure 2). The temporal emissions and trend were mostly consistent with previous studies [3], with an R^2 of 0.93 (Figure S1). In this study, emissions of farmland ecosystems were considered.

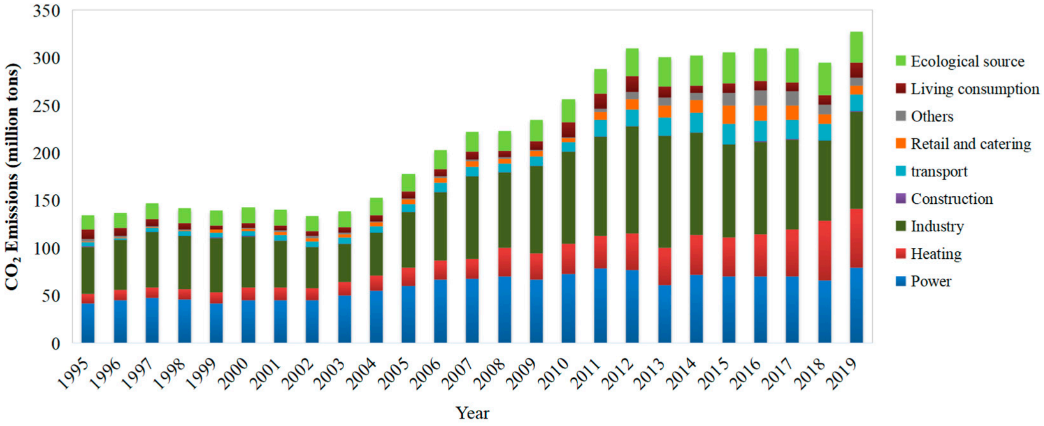

Figure 2. Total CO_2 emissions by sectors from 1995 to 2019 in Heilongjiang Province.

3.1.1. Dominant Energy-Related Sectors

Coal combustion is the dominant source of CO_2 emissions. It contributed to 84.64% of total emissions in 2019. The winter of 2018 was unusually warm, and coal consumption was much lower than in 2017 or 2019, and hence the emissions were obviously lower. Other energy types contributed to 13.91–28.18% of total emissions from 1995 to 2019 (Figure 3).

Energy is utilized by various sectors, including power generation, heating, transportation, agriculture, retail, and domestic consumption, among others. According to computing results, industry and power generation are dominant anthropogenic emission sources and contributed to 33.85% and 33.86% of total emissions in 2005, respectively. Heating and agriculture are important contributors too. The contributions of the heating sector increased gradually, associated with the increased population and heating areas. The contributions of the agriculture sector were stable, and the rates were around 10%. In 2019, industry, power generation, heating, and agriculture contributed to 84.54% of total emissions (Figure 4).

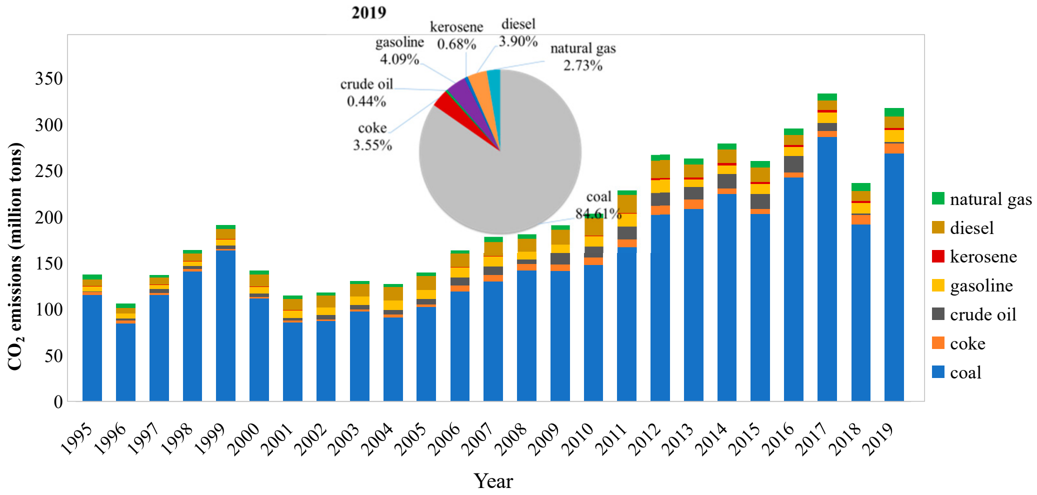

Figure 3. Total energy-related CO_2 emissions in Heilongjiang Province.

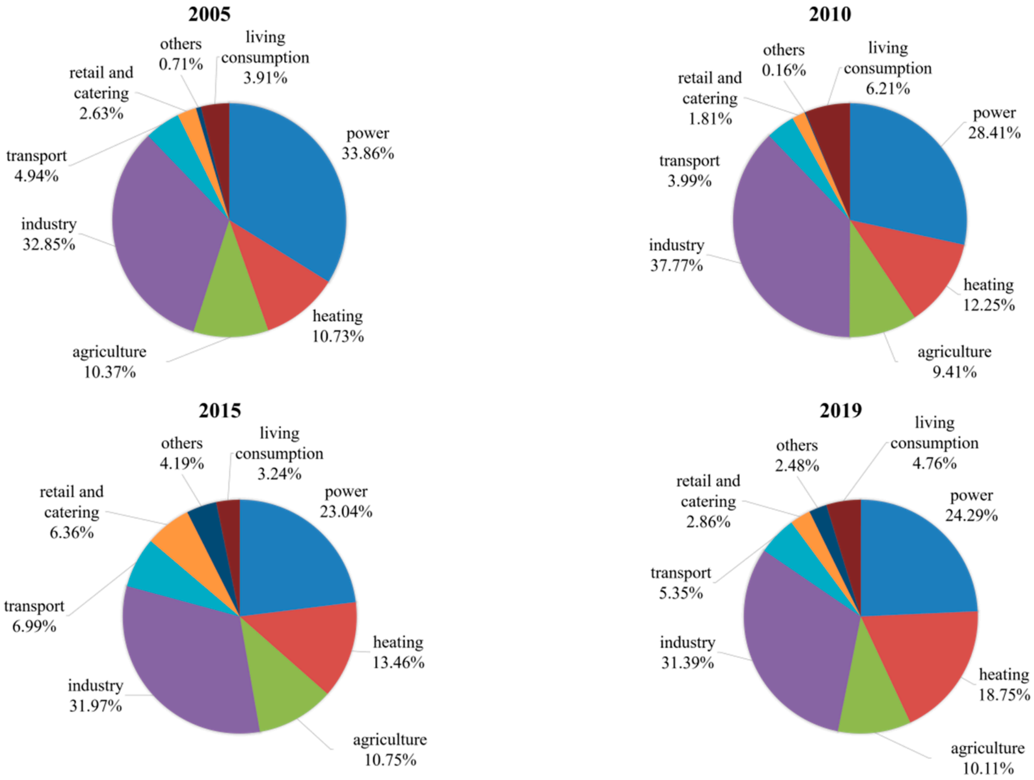

Figure 4. Variations of the CO_2 emissions in Heilongjiang Province by sector.

The industrial sector emits CO_2 through coal combustion and manufacturing processes. For coal combustion, CO_2 emissions rose rapidly from 2005 to 2014. The emissions from raw coal combustion were 169.86 million tons with a contribution rate of 69.09%, which was much higher than the national average [3]. Thereafter, the government paid significant attention to air pollution control. Emissions of CO_2 from coal combustion were abated by the bans and control strategies, falling to 63.5 million tons in 2019.

Moreover, Daqing is the city with the largest oil production in China. As a strong industrial city in Heilongjiang Province, its industrialization is at the forefront of other cities, contributing to 65% of the total provincial CO_2 emissions.

Cement, iron, and ammonia production are typical industrial processes in Heilongjiang Province. From 1985 to 2019, the emissions from cement, iron, and ammonia production all showed a steady upward trend. The CO_2 emissions of iron production were greater than those of cement. Emissions from iron production increased significantly from 2000 to 2013, and then decreased to 175 million tons in 2017. Emissions from cement production increased slightly in 1985–2013, decreased from 2014 to 2017, and then increased again in 2018. Harbin city contributed to 30–40% of CO_2 emissions from the cement sector, while 10–15% of CO_2 emissions came from Qiqihar's cement sector.

Thermal power generation is an important source of CO_2 emissions. Emissions from the thermal power sector rose on the whole from 1995 to 2011, by which time CO_2 emissions reached 78.84 million tons in 2012. Emissions were stable from 2013 to 2018, when they were around 70 million tons. Emissions from the thermal power generation sector rose to 79.57 million tons. From the perspective of cities, Daqing is the largest contributor to CO_2 emissions in the thermal power generation sector. From 2000 to 2014, the contribution rate was about 45% to 65%. The contribution rate of Harbin was stable in the range of 15–25%.

The emissions of the heating sector in Heilongjiang Province are on the rise. Emissions have increased rapidly since 2007, reaching 61.44 million tons in 2019. This indicates that the demand for fossil fuels for heating in Heilongjiang continued to increase. Due to the cold weather in Heilongjiang Province, a larger amount of emissions from the heating sector was noticed. For instance, the contribution of the heating sector in Harbin (9.43%, the capital city of Heilongjiang Province) was about three times higher than that in Shanghai (2.9%) [24]. From the perspective of the city, Daqing consumed the largest amount of fossil fuel for heating, followed by Harbin and Mudanjiang.

Driving forces refer to energy, GDP, and populations, affecting CO_2 emissions. In this study, carbon intensity is applied to CO_2 emissions (million tons) per unit GDP (million yuan, RMB). The carbon intensity reduced over time, which was consistent with the tendency of the energy intensity. The total CO_2 emissions and CO_2 emissions per capita in Heilongjiang Province during the period of 1995–2003 were in a stable state; from 2004 to 2011, both figures rose sharply; after 2011, the total carbon emissions were stable, but due to the decline in the population, the per capita emissions still showed an upward trend (Figure 5). The population is a significant factor in CO_2 emissions, which was consistent with the analysis based on the 2011–2016 data in a previous study [27]. The warm winter of 2018 led to a significant decline in per capita carbon emissions.

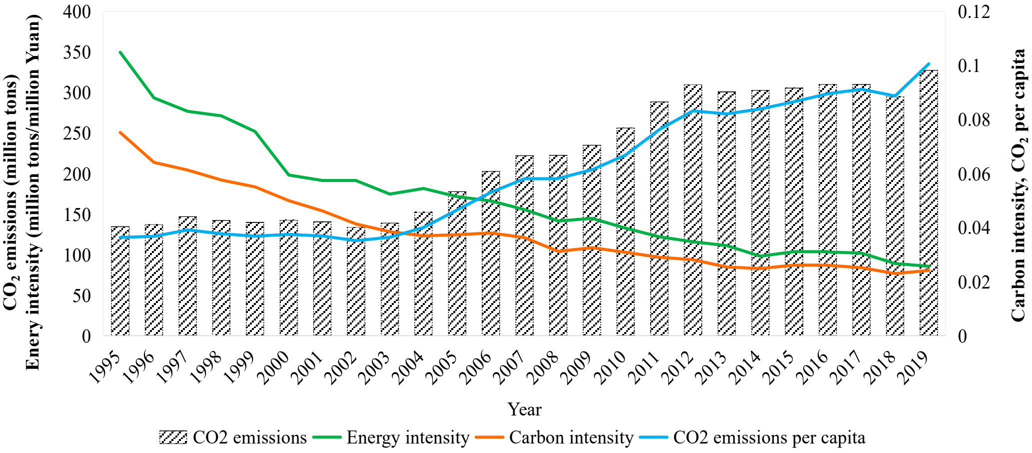

Figure 5. Effects of driving forces on CO_2 emissions (population, energy intensity, carbon intensity).

3.1.2. Emissions from Ecological Sectors

The farmland ecosystem has the dual role of being both a carbon source and a carbon sink. In general, CO_2 is emitted from the processes of five farmland sectors in Heilongjiang Province, including applications of chemical fertilizer, pesticides, agricultural films, farmland irrigation, and agricultural machinery. Overall, CO_2 emissions rose smoothly until 2016, reaching 23.12 million tons. The CO_2 emissions estimated in Yunnan Province were 35.26 million tons in 2015, which was higher than that in Heilongjiang province [9]. From 2017, the emissions showed a downward trend, owing to the reduction in fertilizer usage.

The decreasing trend of farmland ecosystem CO_2 emissions was also found in Beijing since 2004, at a rate of 5.5% annually from 2004 to 2012 [28].

Chemical fertilizer (nitrogen fertilizer, phosphate fertilizer, potash fertilizer, and compound fertilizer) contributed to 60–70% of the total CO_2 emissions from the farmland ecosystem sector, which is the biggest contributor, followed by farmland irrigation, pesticides, agricultural film, and machinery [11,28]. The contribution of fertilizer in Heilongjiang Province was consistent with that in Beijing (63.5%, 2004–2012) and 10–20% more than that in Chongqing (approximately 50%, 2006–2015). From the perspective of spatial distribution, the emissions of Harbin, Suihua, Qiqihar, and Jiamusi were about 2.4, 1.73, 1.71, and 1.55 million tons, respectively, with 62.59% of total emissions coming from the fertilizer administration process in 2019.

Irrigation is the second biggest contributor to the farmland ecosystem sector in many regions of China, including Yunnan Province, Beijing, and Chongqing [10,11,28]. In Heilongjiang province, the emissions from irrigation increased gradually from 1996, contributing up to 28% of total emissions from the farmland ecosystem sector. The emissions in Qiqihar and Harbin are much higher than those of other cities, with 40% of total emissions being contributed by the irrigation process. In sum, 28% of the total CO_2 emissions of Daqing and Jiamusi came from the irrigation process.

Applications of pesticide, agricultural machinery, and agricultural film emitted 5%, 6%, and 4% of total CO_2 in the farmland ecosystem sector in 2019, reaching 1.16, 1.37, and 0.92 million tons, respectively.

3.2. City-Level CO_2 Emissions in Heilongjiang

The total emissions of carbon dioxide in cities in Heilongjiang Province all increased over time, from 1995 to 2019. Emissions from Daqing were 35.38–108.21 million tons, making it the largest contributor in Heilongjiang Province (Figure 6). However, the growth rate was 4.77% annually from 1995 to 2019, which was much lower than the mean growth rates of cities that ranged from 8.56 to 9.90% for 1990 to 2010 [1]. In Daqing, the power, heating, and industrial sectors are relatively developed, and the combustion of fossil fuels in these three sectors is the dominant anthropogenic source. The main sources of carbon dioxide emissions in Harbin are cement production and farmland ecosystems. The emissions form Harbin (the capital of Heilongjiang province) were up to 69 million tons in 2019. Compared to other capital cities, the emissions of Harbin (41.44 million tons) were much lower than those of Nanjing and Guangzhou in 2010, but twice as high as those from Shanghai (18.87 million tons). The differences can be attributed to the characteristics of energy consumption in these cities [6]. Emissions in Qiqihar and Mudanjiang followed similar trends, with emissions of 22 million tons and 29 million tons in 2019, respectively. The emissions of Jixi, Heihe, Suihua, and Jiamusi were in the range of 3 million to 10 million tons. The emissions of the other cities were relatively low, at less than 1 million tons.

According to the data of other cities, the CO_2 emissions of Guangzhou, Handan, Tangshan, Changsha, Shenyang, Hohhot, Weifang, and Xi'an [3] were higher than those of Harbin, owing to the characteristics the development of the cities (Figure 7). The emissions of Hefei, Chengdu, Zunyi, Nanning, and Shenzhen, etc., are lower those of than Harbin, because of the energy consumption. The heating sector may be the significant factor that makes the most difference.

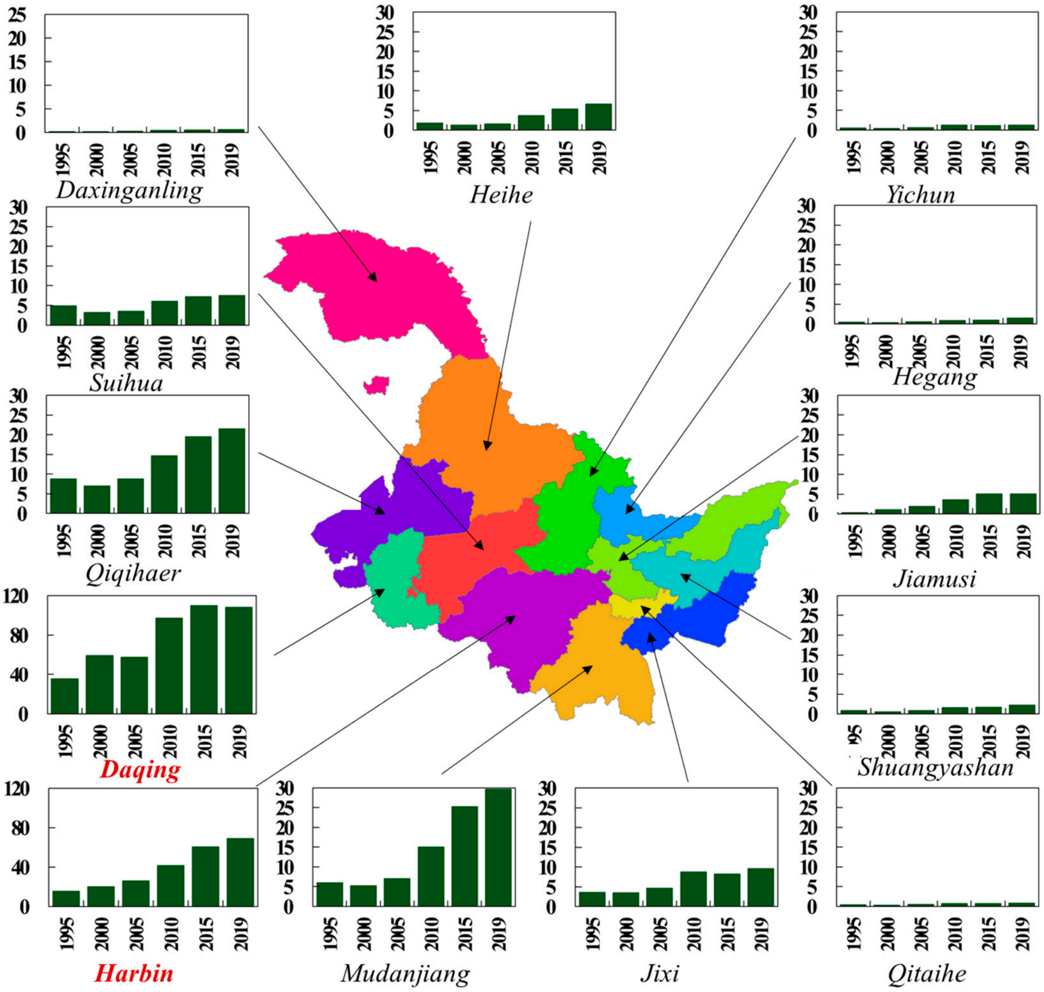

Figure 6. Variations of the city-level CO_2 emissions in 1995, 2000, 2005, 2010, 2015, and 2019 (unit: million tons).

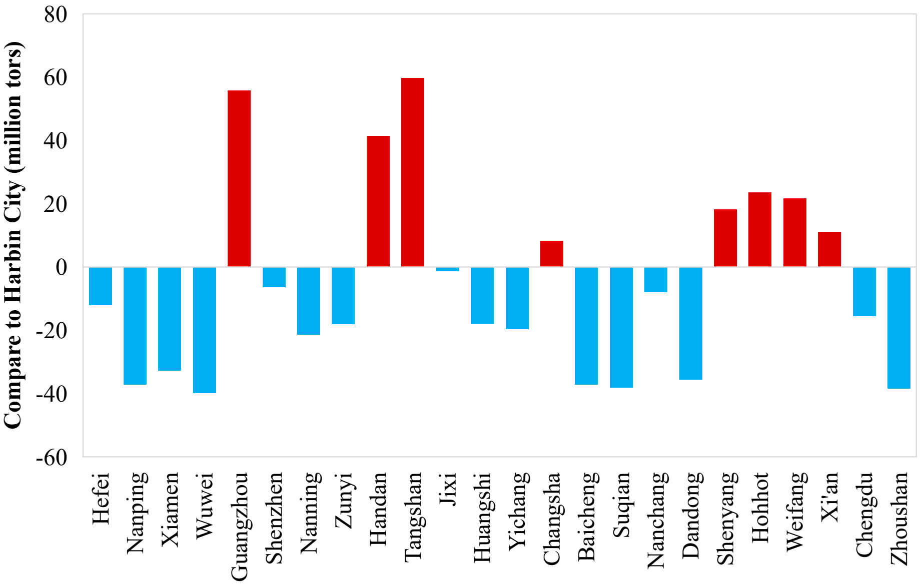

Figure 7. Comparisons of CO_2 emissions to other cities, 2010.

3.3. *CO_2 Absorption by Ecosystem*

3.3.1. CO_2 Absorption from the Farmland Ecosystem

Heilongjiang Province is an important grain-producing province. The farmland ecosystem is a significant carbon sink with a higher capacity. The overall carbon dioxide absorption has increased rapidly since 2004. The amount of absorption reached 343.91 million tons in 2019. Compared to Yunnan, the absorption was more than an order of magnitude higher than that of Yunnan province (20.31 million tons) in 2015 [10]. Hence, Heilongjiang Province would provide a considerable regional carbon sink.

In terms of crop types, the planting area and production of corn in Heilongjiang Province rank first in China, and the total CO_2 absorption of corn accounts for 49.92% of the total farmland absorption in 2019. Rice is the second-largest contributor to CO_2 absorption according to crop types, accounting for about 36.79% of the absorption. Beans absorbed about 12% of CO_2 in the farmland sector, while other crops (vegetables, fruits, grains, etc.) absorbed 2.56% of the total. In the southwest region of China, absorption of corn are higher than those of rice. For instance, rice contributed to 41% and 33% of the total CO_2 absorption in Yunnan and Chongqing, respectively, which were higher than those of corn (39% in Yunnan, 25.42% in Chongqing) [10,11].

Before 1997, the absorption in Qiqihar, Heihe, and Suihua was much higher than in other cities in Heilongjiang Province. Then, the absorption of Harbin increased rapidly, contributing to 15.91% of total absorption and ranking first in 2019; Qiqihar ranked second, and the proportion of total absorption was 15.43%, followed by Jiamusi (10%), Daqing (8%), etc.

3.3.2. CO_2 Absorption from Living Wood

Living wood refers to the trees, scattered wood, and sparse forest trees. The net absorption of CO_2 by living wood in Heilongjiang Province increased gradually, with a growth rate of about 10% (Figure 8). The annual absorption was 69.3 million tons.

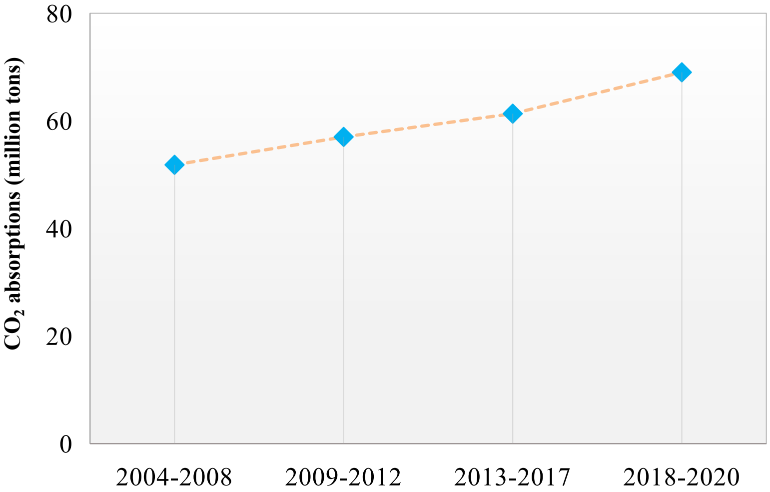

Figure 8. The CO_2 absorption by living wood (2004–2020).

3.4. *Impacts on Ambient CO_2*

Monthly CO_2 mixing ratios of the in situ measurements at Longfengshan Background Station (44.73 N, 127.6 E, 331 a.s.l.) in Heilongjiang Province, which is the only WMO/GAW station in the northeastern China plain, observing atmospheric greenhouse gases. The atmospheric CO_2 mole fractions were continuously measured by a Cavity Ring Down Spectrometer (CRDS; Picarro Inc., Santa Clara, CA, USA) [1]. A robust local regression mathematical method was applied to distinguish the mixing ratio in the background and polluted conditions [29]. The long-term trend was estimated based on a linear curve fitting the CO_2 background mixing ratios.

The annual means of CO_2 concentrations rose gradually (Figure 9). Peaks appeared in winters, influenced by increased energy consumption for power generation, heating, and industrial boilers. Moreover, trees lose their leaves, and agriculture in the field ceases. Valley values appeared in the summers. In the summer, energy consumption is much lower than in the winter, and all trees and crops help to absorb CO_2. The diurnal amplitude at Longfengshan Background Station is 50.6 ± 7.0 ppm in summer, which is the largest value among the four WMO/GAW stations in China [7].

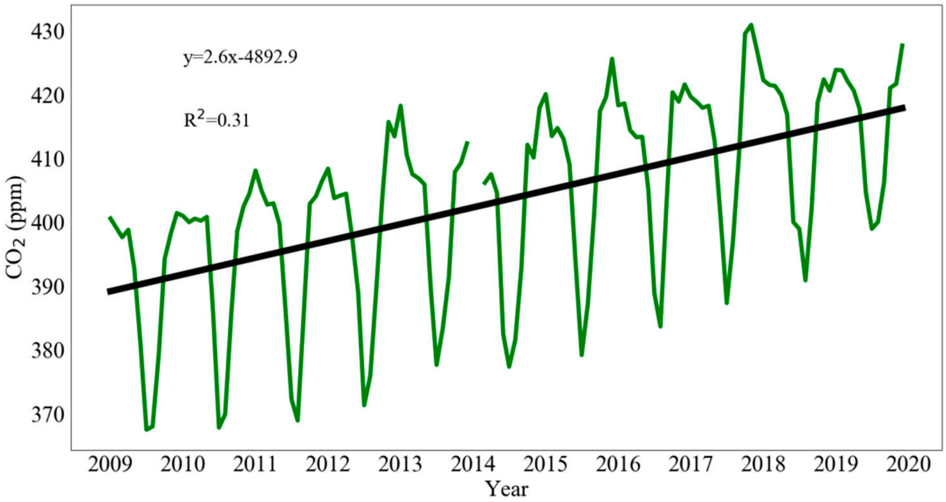

Figure 9. Monthly CO_2 concentrations in Heilongjiang Province (2009–2019).

4. Conclusions

This study focused on quantifying CO_2 emissions and environmental characteristics behaviors in the coldest region of China. The results provide valuable insights into the specialized structure of energy consumption in the cold region, where the industrial sector, thermal power generation, and heating were identified as the dominant emission sectors. Long winters in the region resulted in a large amount of CO_2 emissions, which were primarily influenced by the heating sector and farmland ecosystem. Emissions of cities were distinct according to the driving forces of energy, population, agriculture and natural emission sources.

This study highlighted the importance of national and regional air pollution control strategies in mitigating CO_2 emissions. The city of Harbin in Heilongjiang Province has successfully reduced CO_2 emissions by replacing smaller heating boilers with more efficient and cleaner technologies. However, coal consumption remains a significant contributor to the increase in CO_2 emissions in recent years, necessitating the adoption of advanced technologies for CO_2 emission control and the use of clean alternative energies to resolve bottleneck issues in the near future.

This study also found that GDP and population were significant driving forces affecting CO_2 emissions, with carbon intensity applied to CO_2 emissions per unit GDP reducing over time. However, per capita emissions continued to show an upward trend despite stable total carbon emissions, primarily due to a decline in population.

Overall, this study provides valuable insights into the city-level CO_2 emissions and sheds light on the investigation of the proper methods to compile city-level emissions in cold regions to better understand the environmental behaviors of greenhouse gases and CO_2 emissions. It underscores the need for continued research on city-level scaled emission inventory and model reliability analysis to facilitate more efficient ways of mitigating climate change [5,30–32]. Additionally, the adoption of advanced technologies for CO_2 emission control and clean alternative energies is essential to achieve long-term sustainable development goals [33–35].

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/pr11051336/s1, Figure S1: Correlation of CO_2 emissions compared to previous studies; Table S1: Ratios of upper and lower emission factors; Figure S2: Sensitivity analysis of CO_2 emissions.

Author Contributions: Writing—original draft preparation, W.S.; writing—review and editing, W.S., R.C., Y.Z. and M.W.; Investigation, W.Y., M.W. and C.L.; Data curation, Z.Z., R.C., X.W., M.L. and D.Y.; Methodology, Z.Z., W.Y. and Z.G.; Supervision, W.S. and D.Y.; conceptualization, Y.Z.; formal analysis, X.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (51778181), and Open Project of State Key Laboratory of Urban Water Resource and Environment, Harbin Institute of Technology (No. ES201908).

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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